

## SILICON AND MAGNESIUM IN PLANETARY NEBULAE

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ABSTRACT

The IUE satellite spectra of some planetary nebulae show features due to silicon and magnesium: Si III]  $\lambda\lambda$  1883, 1892; Si IV  $\lambda\lambda$  1394, 1403; Mg II  $\lambda\lambda$  2796, 2804 and [Mg V]  $\lambda\lambda$  2784, 2929. With the aid of modeling techniques, we can find the corresponding elemental abundances, which have not hitherto been known for planetary nebulae. In addition to previous observations of NGC 7662 and IC 418, we now have data for NGC 2440, Hu 1-2, IC 2003 and IC 2165. Silicon appears depleted by up to an order of magnitude relative to the sun. Large variations of magnesium abundance are found, which are likely to reflect differing degrees of depletion due to grain formation. Such observations may offer new insight into the formation of interstellar grains.

INTRODUCTION

It is known that elements such as Mg, Al, Si, Ca and Fe, which form refractory compounds, are strongly depleted in the interstellar medium, presumably by the formation of grains (ref.1). We would like to know if such depletions occur in planetary nebulae, for this would be direct evidence of grains within the ionized gas and the pattern of depletion could provide information about the formation and composition of the dust. Shields (ref. 2) has shown that Fe is depleted in a number of planetary nebulae; otherwise little is known about the abundance of refractory elements in these objects.

OBSERVATIONS

## SILICON

Lines of Si III]  $\lambda$ 1882.7,  $\lambda$ 1892.0 and Si IV  $\lambda$ 1393.8,  $\lambda$ 1402.8 are seen in the IUE spectra of planetaries. The Si III] lines are close to the strong C III]  $\lambda$ 1906.7,  $\lambda$ 1908.7 doublet, while the Si IV lines are intermeshed with the O IV]  $\lambda$ 1397.2, 1399.8, 1401.2, 1404.8, 1407.4 quintet. A high-dispersion spectrum of NGC 7662 (SWP 4106 - 400 min.) obtained by Dr. S.R. Heap clearly shows the individual components of Si III], Si IV and O IV]. For most nebulae, the Si lines are too faint to observe at high-dispersion, so we must rely on low-dispersion data. Low-dispersion observations of NGC 7662 with the small aperture (which gives somewhat better resolution than the large aperture) show the Si III]  $\lambda$ 1883 and Si IV  $\lambda$ 1394 lines (ref. 3). (The Si III]  $\lambda$ 1883/ $\lambda$ 1892 ratio, like C III]  $\lambda$ 1907/ $\lambda$ 1909, is density-sensitive, with a low density limit of about 1.5. In NGC 7662 this ratio is seen at high-

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dispersion to be greater than unity; thus for objects where we only observe the  $\lambda 1883$  line we have assumed the low-density ratio.) We have measured the flux in Si III  $\lambda 1883$  in four additional nebulae with the large slot in low dispersion. The results are presented in Table 1. For NGC 2440, the photowrite shows the spatially extended image of the  $\lambda 1883$  line.

Si IV is usually substantially weaker than O IV]. When the Si IV contribution to the blend becomes comparable to O IV], the feature shows a distinct blueward shift, since the  $\lambda 1394$  line is twice the intensity of  $\lambda 1403$ . This effect is observed in Hu 1-2, the nebula with the largest Si III] intensity.

## MAGNESIUM

The Mg II  $\lambda 2796.4$ ,  $\lambda 2803.5$  doublet is a strong feature in a few planetaries, e.g. IC 418 (ref. 4). It has also been observed in the high-excitation object NGC 7027 (ref. 5). We observe faint Mg II emission in IC 2165 and NGC 2440. In the latter case, the lines are also seen at high dispersion (LWR 6257).

Lines of [Mg V] at  $\lambda 2783.9$  and  $\lambda 2929.2$  were identified in NGC 7027 (ref. 5). The  $\lambda 2784/\lambda 2929$  intensity ratio should be 3.6. We see the [Mg V]  $\lambda 2784$  line very clearly in our high-dispersion spectrum of NGC 2440 and there is also a feature of the expected intensity at  $\lambda 2929$ . The [Mg V] lines have the same width as the other nebular lines.

We have measured the [Mg V]  $\lambda 2784$  flux in the low dispersion spectra of three objects: NGC 2440, IC 2165 and Hu 1-2. In IC 2165 there is clear stratification: the [Mg V] image is almost stellar while the Mg II image is very extended. This is also seen when the spectrum is traced with different slit heights.

## INTERPRETATION

### MODELS

We have constructed preliminary models of three nebulae. Details of the atomic data adopted and of the numerical procedures employed will be given elsewhere (ref. 6). It should be noted that the photoionization cross section of  $\text{Mg}^+$  (ref. 7) is unusually small (0.28 Mb at threshold; cf. 6.3 Mb for  $\text{H}^0$ ). This leads to a higher fractional abundance of  $\text{Mg}^+$  than for other singly ionized species. The  $\text{Si}^{+2}$  and  $\text{Si}^{+3}$  photoionization cross sections we use (ref. 8, 9) are also many times smaller than the quantum defect values sometimes employed (e.g., ref. 10).

In Table 2 model predictions for IC 2165 and NGC 2440 are compared with observations. The model for IC 2003 is given elsewhere in this volume (ref. 11), where the CNO abundances of the three nebulae are discussed. All models employ blackbody stellar fluxes and simple density distributions. The defining parameters for the models of IC 2003, IC 2165 and NGC 2440, respectively, are as follows: Stellar temperature: 100,000 K; 135,000 K; 180,000 K. Stellar luminosity:  $1.3 \times 10^4 L_\odot$ ;  $2.6 \times 10^3 L_\odot$ ;  $1.9 \times 10^3 L_\odot$ .

Adopted distance: 7.6 kpc; 2.8 kpc; 2.3 kpc. Inner and outer radii: 0.06-.12 pc; 0.007-0.055 pc; 0.022- 0.122 pc. Filling factor: 0.043; 0.5; 0.14. Hydrogen density of filled volume: constant at  $10^4 \text{ cm}^{-3}$ ; constant at  $7.2 \times 10^3 \text{ cm}^{-3}$ ;  $n_H \propto r^{-1}$ , decreasing from  $1.4 \times 10^4 \text{ cm}^{-3}$  to  $2.75 \times 10^3 \text{ cm}^{-3}$ . He/H ratio: 0.13; 0.13; 0.154.

We attempted to fit the [O III]  $\lambda 5007/\lambda 4363$  temperature sensitive ratio and to match the overall ionization structure even if a fit to the total flux in some of the emission lines could not be achieved. We can use these models as a basis for the interpretation of the Si and Mg features.

## SILICON

The silicon abundances in our models were adjusted to match the observed Si III]  $\lambda 1883$  intensity. Table 1 shows the resultant Si/O ratios. The solar value of Si/O is 0.052 (ref. 12, 13). Thus silicon would appear to be depleted by up to an order of magnitude in these nebulae. We do not yet have a model of Hu 1-2, but it is likely that the Si depletion for this object is less than for the others.

It can be seen from Table 2 that the Si IV intensities which result from our adopted abundances are consistent with the observational result that O IV] is the dominant contributor to the  $\lambda 1400$  blend. Because the collisional excitation rate for the  $\text{Si}^{+3}$  ion is 36 times larger than that of the  $\text{O}^{+3}$  ion, a Si/O ratio near solar would lead to the domination of this feature by Si IV; this is not observed even in Hu 1-2.

## MAGNESIUM

Because of the small photoionization cross section for  $\text{Mg}^+$  and the large collisional cross section for Mg II  $^2\text{S}-^2\text{P}^0$  ( $\Omega \sim 17$ ), we would expect Mg II  $\lambda 2800$  to be prominent in the UV spectra of planetary nebulae unless Mg is strongly depleted. In IC 418,  $\lambda 2800$  is strong and an approximately solar Mg/H ratio has been derived for this object (ref. 4). On the other hand, in the Orion nebula (which is of similar excitation),  $\lambda 2800$  is not seen. This implies an order of magnitude depletion of Mg (ref. 14). A depletion is also implied by the absence of Mg II  $\lambda 2800$  in high excitation planetaries; e.g. NGC 7662 (ref. 15,6). The fact that Mg II  $\lambda 2800$  is not observed in most of the nebulae examined by Boggess, Feibelman and McCracken (ref. 16) implies that the depletion is widespread.

The situation becomes more complex, however, when we consider planetaries in which [Mg V] is observed. An analysis of NGC 7027 by Péquignot and Stasińska (ref. 17) showed that no single Mg abundance could simultaneously reproduce the intensities of both [Mg V]  $\lambda 2784$  and Mg II  $\lambda 2800$ . They were led to propose an abundance gradient, with Mg/H near solar in the inner region of the object and strongly depleted in the outer region.

We find just the same situation in IC 2165 and NGC 2440. The Mg abundances of the models in Table 2 have been adjusted to match the observed Mg II  $\lambda 2800$  fluxes. The resultant Mg/H ratios are  $10^{-6}$  for IC 2165 and  $8 \times 10^{-7}$  for NGC 2440, compared to the solar Mg/H ratio of  $4.2 \times 10^{-5}$  (ref. 13).

However, if we were to adjust Mg/H to match the [Mg V]  $\lambda$ 2784 line, the ratios would be  $2.5 \times 10^{-5}$  for IC 2165 and  $3.5 \times 10^{-5}$ , not significantly different from the solar value. (Compounding the difficulty is the fact that the models, even with the low abundances adopted, produce a Mg I]  $\lambda$ 4571 intensity much greater than observed. There might be charge-transfer effects which would prevent the existence of as much Mg<sup>0</sup> in the ionized gas as the models predict, however.)

Péquignot and Stasinska propose that the carbon-rich nature of NGC 7027 is responsible for locking up the O in CO at the time of grain formation, so the Mg condenses as a metal rather than some more refractory compound, and thus can later evaporate in the inner regions of the nebula. This scheme might also be invoked for IC 2165, but in the case of NGC 2440, we find that C/O < 1 (ref. 11).

In any case, unless our ideas of the ionization structure for Mg are completely in error, further study of this "Mg II-[Mg V] anomaly" in planetary nebulae promises us insights into the formation and/or destruction of grains in differing chemical environments.

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TABLE 1 -- S1 III]  $\lambda$ 1883 FLUXES AND S1/O RATIOS

	IC 2003	IC 2165	NGC 2440	Hu 1 - 2
F(S1 III] $\lambda$ 1883) erg/cm <sup>2</sup> /s	4.10 <sup>-14</sup>	4.10 <sup>-14</sup>	1.7x10 <sup>-13</sup>	6.x10 <sup>-14</sup>
I(S1 III] $\lambda$ 1883,92) <sup>(a)</sup>	3.0	3.2	5.8	11.
(S1/O) Abundance Ratio	0.006	0.006	0.005	--

(a) Relative to I(H $\beta$ ) = 100, corrected for reddening (ref. 11);  
I( $\lambda$ 1883)/I( $\lambda$ 1892) = 1.5 assumed.

TABLE 2. LINE INTENSITIES: OBSERVATIONS AND MODEL PREDICTIONS.

LINE	OBS. #	IC 2165 MODEL	$t_{ion}^*$	OBS. #	NGC 2440 MODEL	$t_{ion}^*$
$\lambda 1241$ N V	45.	40.	1.81	100.	95.	1.61
$\lambda 1394,03$ Si IV		4.3	1.50		5.6	1.55
$\lambda 1401,5$ O IV]	39.	18.3	1.68	54.	28.4	1.58
$\lambda 1406,17$ S IV]		1.7	1.50		1.2	1.55
$\lambda 1485$ N IV]	47.	50.	1.57	220.	170.	1.57
$\lambda 1549$ C IV	970.	960.	1.55	500.	585.	1.57
$\lambda 1640$ He II	260.	290.	1.73	350.	480.	1.56
$\lambda 1664$ O III]	33.	35.	1.42	42.	42.	1.41
$\lambda 1750$ N III]	37.	29.	1.42	170.	170.	1.44
$\lambda 1883,92$ Si III]	3.2	3.2	1.47	5.8	5.8	1.52
$\lambda 1908$ C III]	850.	725.	1.43	750.	660.	1.40
$\lambda 2328$ C II]	81.	33.	1.40	97.	80.	1.15
$\lambda 2424$ [Ne IV]	110.	83.	1.62	160.	160.	1.49
$\lambda 2470$ [O II]	--	--	--	17.	22.	1.20
$\lambda 2784$ [Mg V]	5.2	0.21	1.87	8.3	0.19	1.60
$\lambda 2800$ Mg II	6.4	6.2	1.40	3.9	3.8	1.21
$\lambda 3426$ [Ne V]	63:	65	1.78	140:	134.	1.57
$\lambda 3727$ [O II]	62.	55.	1.38	230.	310.	1.20
$\lambda 3869$ [Ne III]	110.	150.	1.41	140.	140.	1.26
$\lambda 4267$ C II	0.46	0.15	1.43	0.38	0.18	1.40
$\lambda 4363$ [O III]	22.	18.	1.42	28.	22.	1.41
$\lambda 4571$ Mg I]	0.6	5.1	1.39	0.2	5.4	1.18
$\lambda 4686$ He II	42.	40.	1.73	58.	68.	1.56
$\lambda 4861$ H $\beta$	100.	100.	1.51	100.	100.	1.46
$\lambda 5007$ [O III]	1190.	920.	1.42	1500.	1200.	1.41
$\lambda 5200$ [N I]	--	--	--	13.	30.	1.00
$\lambda 5755$ [N II]	0.5:	2.1	1.38	17.	31.	1.19
$\lambda 5876$ He I	11.	11.6	1.42	11.3	13.6	1.31
$\lambda 6300$ [O I]	3.2	0.6	1.37	24.	29.	1.05
$\lambda 6312$ [S III]	1.7	2.0	1.41	2.3	1.9	1.38
$\lambda 6584$ [N II]	45.	54.	1.38	970.	1200.	1.19
$\lambda 6723$ [S II]	6.	5.3	1.39	29.	28.	1.16
$\lambda 7325$ [O II]	6.	8.9	1.38	16.	27.	1.20

#The UV observations are discussed in ref. 11. The optical data is from ref. 18 and 19. Intensities have been corrected for reddening (ref. 11).

#Optical data from ref. 18, 20 and 21.

\*Model temperature weighted by  $N_e N_{ion}$ , in units of  $10^4$  K. See ref. 11.

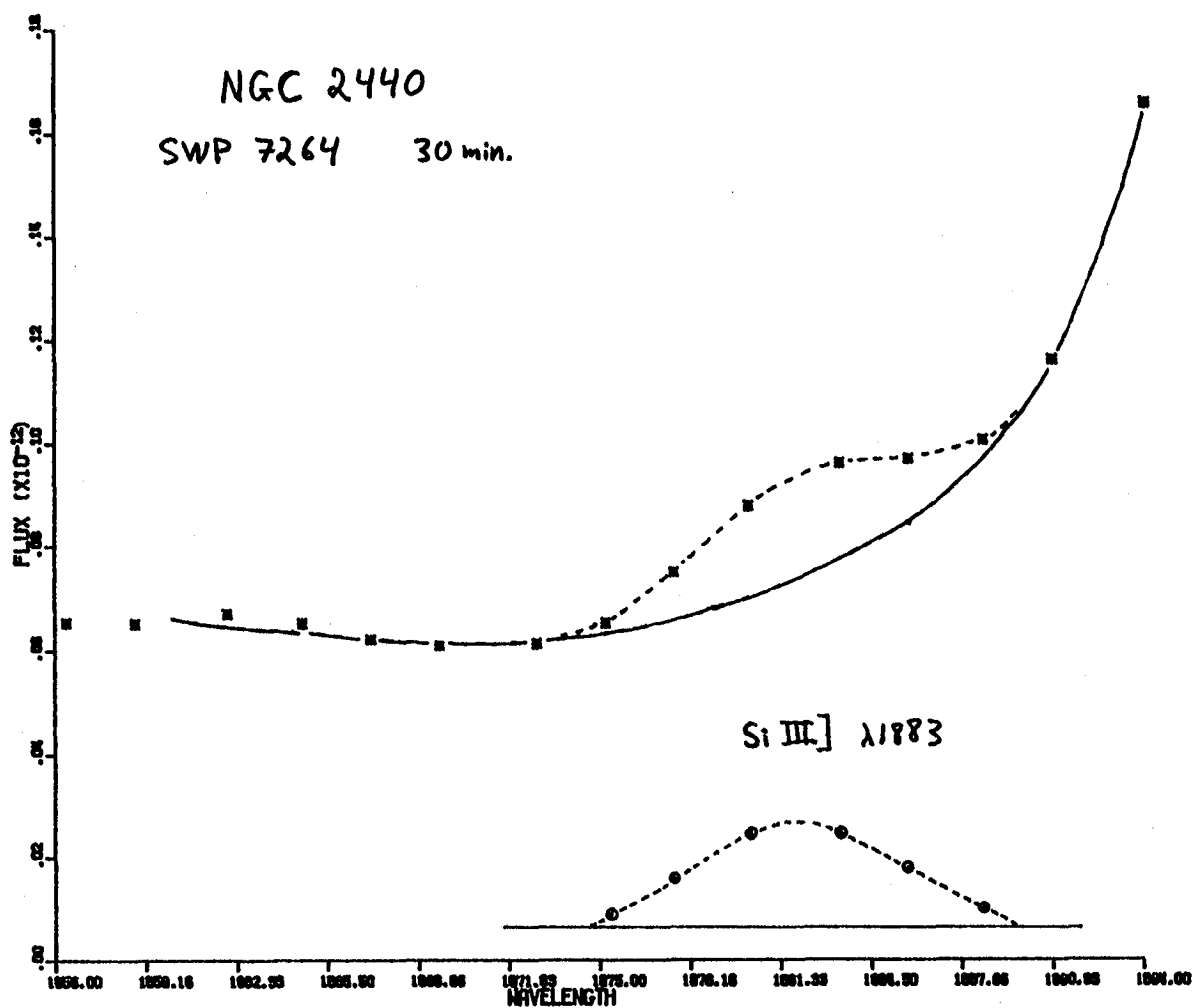


Fig. 1 - The Si III]  $\lambda 1883$  feature on the wing of C III]  $\lambda 1909$  in NGC 2440.

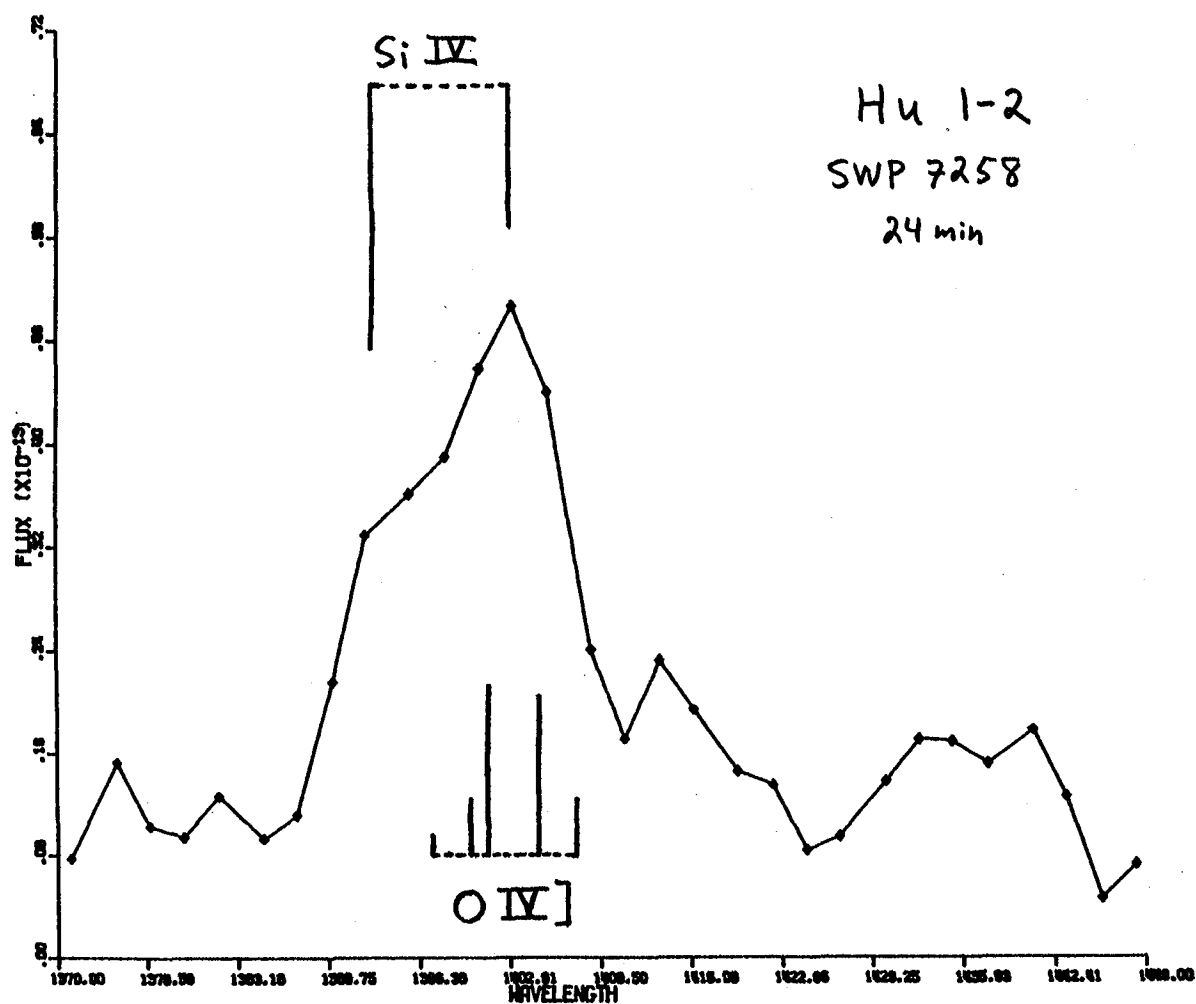


Fig. 2 - The  $\lambda 1400$  Si IV - O IV] blend in Hu 1-2. The length of the vertical lines indicates the theoretical relative intensity of the line component.



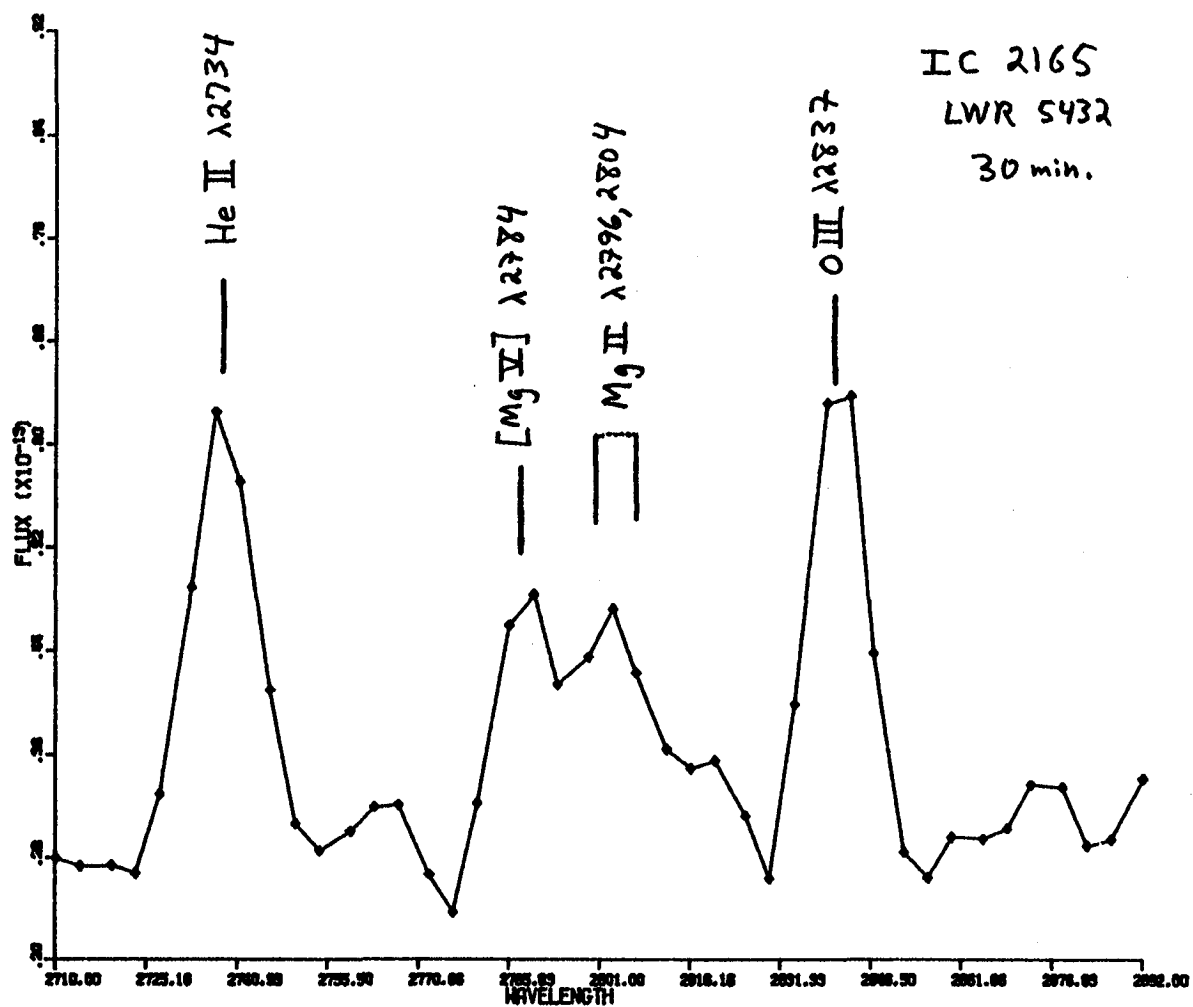


Fig. 3 - The Mg lines in IC 2165 at low resolution.